Spectroscopic evidences of quantum critical charge fluctuations in cuprates

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Abstract

We calculate the optical conductivity in a clean system of quasiparticles coupled to charge-ordering collective modes. The absorption induced by these modes may produce an anomalous frequency and temperature dependence of low-energy optical absorption in some cuprates. However, the coupling with lattice degrees of freedom introduces a non-universal energy scale leading to scaling violation in low-temperature optical conductivity.

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There is substantial evidence that charge and spin inhomogeneities are present in underdoped superconducting cuprates, where charge-ordering (CO) takes place with formation of stripe or checkerboard textures [for a review see, e.g., Refs. [1,2]]. On the other hand it has also been proposed that a quantum-critical instability (quantum critical point, QCP) takes place around optimal doping [1,3,4,5], but the type of order that establishes in the low-temperature underdoped region is still controversial. Our proposal of spatial CO [5] unifies the issue of quantum criticality with the issue of charge inhomogeneities. According to Ref. [5], the CO-QCP can naturally arise in a model where the density of strongly interacting electrons is locally coupled to a dispersionless phonon. For realistic model-parameters the CO instability first occurs along the $(1,0)$ or $(0,1)$ directions (i.e., along the Cu-O bonds) at wavevectors of order $|\mathbf{q}_c| \approx \pi/5 \div \pi/4$. Accordingly, near the QCP the fermionic quasiparticles are coupled to the low-energy CO collective modes (CM). Strong effects occur near the "hot" spots at the Fermi surface, which are mutually connected by $\mathbf{q}_c$ and reside near the $(\pm\pi,0)$ and $(0,\pm\pi)$ points. This is rather similar to the case of antiferromagnetic spin fluctuations, where, however, the critical wavevectors are $\mathbf{q}_s \approx (\pi,\pi)$. The phonon-driven CO instability has the additional advantage that the phonon energy introduces a built-in energy scale, which provides a natural framework for non-trivial isotopic effects [9,10]. It should be kept in mind that several causes like, e.g., pairing and disorder, together with the nearly twodimensional character of the cuprates, may prevent the formation of static long-range CO. This gives a dynamical character to the excitations accounting for the strong variations of the pseudogap temperature T^* depending on the timescale of the probes [9]. Furthermore, the charge CM provide a "cheap" reservoir of excitations, which can easily affect the various spectroscopic probes. These effects have been extensively studied within phenomenological models, where the fermionic quasiparticles are coupled to the CO-CM. In this way specific features in ARPES (e.g., the fermionic self-energy [7], the kink [8] and the isotopic dependence of the dispersions [10]), and in Raman [11], have been coherently explained. Remarkably, in those cases where the

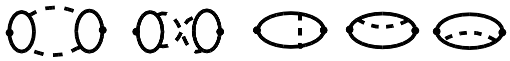

Fig. 1. Diagrams for the current-current response function. The full dots represent the current vertices, the solid and dashed lines represent quasiparticle and CO-CM propagators respectively.

spectroscopic probe provides informations on the momenta of the excitations (ARPES and Raman), the spectra agree with the theoretical predictions only for the CM momentum dependence corresponding to CO excitations [$\mathbf{q}_c \approx (\pi/2, 0), (0, \pi/2)$] and *not* to spin excitations [$\mathbf{q}_s \approx (\pi, \pi)$].

Recently we attacked the *microscopic* calculation of the optical conductivity within a conserving approximation. For the clean case the diagrams correcting with the CO-CM excitations the bare current-current response function are reported in Fig. 1. Here we limit ourselves to the clean case to put in evidence the effects of critical CM's and of their typical energy scales. We use the standard Kubo formula to derive the conductivity directly from the current-current response function. It is well known that this perturbative approach without suitable diagram resummations [12] fails in transforming the δ-like conductivity at zero frequency into a regular Drude peak. Keeping this in mind we concentrate on the finite-frequency conductivity, which is adequately described by our conserving perturbative scheme. To treat the clean case it must be considered that the CM's are not purely electronic (otherwise the total electronic momentum would be conserved and the conductivity at finite frequency would identically vanish), but involve phonon degrees of freedom, which modify the purely relaxational form of the CO-CM

$$D(\mathbf{q}, \omega_n) = -g^2 \left[\nu(\mathbf{q} - \mathbf{q}_c)^2 + |\omega_n| + \omega_n^2/\overline{\Omega} + m \right]^{-1}$$

where ω_n are bosonic Matsubara frequencies, g is the quasiparticle-CM coupling, ν is an electronic scale, and $m \propto \xi^{-2}$ is the CO-CM mass proportional to the inverse square correlation lenght of the CO transition. $\overline{\Omega}$ is the parameter relating electronic and phononic scales [13] and it encodes the dynamical nature of the phonon propagators. For $\overline{\Omega} < \infty$ a finite dynamical response function arises, with various regimes for the optical conductivity curves. Here, assuming a CM-mass linearly scaling with temperature, as appropriate for the quantum-critical regime, we calculated the finite frequency contribution $\sigma(\omega)$. Spectral weight is generically subtracted from the low-frequency part of the spectra and upon decreasing T peaks appear. For $m < \overline{\Omega}$ the peak saturates at $\omega \sim \overline{\Omega}$ and there is no relation between m and the peak position. On the contrary for $m > \overline{\Omega}$ (see Fig. 2) the peak occurs at $\omega \sim m$ and accordingly shifts to lower frequencies with increasing total intensity. This would be a distinctive signature of a quasi-critical CM in $\sigma(\omega)$.

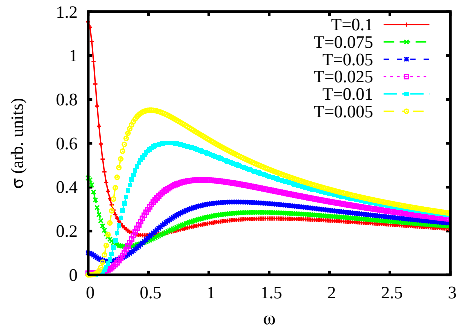

Fig. 2. Optical conductivity for a system of quasiparticles coupled to CO-CM modes in the quantum-critical regime with $m = 30T$. The total intensity depends on the parameter $\overline{\Omega}$ and energy units are chosen to give $\overline{\Omega} = 0.1$.

In summary, from our analysis one sees that, despite their neutral character, CO-CM may strongly affect the optical conductivity. However, the spectra are non universal and their scaling properties only occur in specific regimes.

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